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Theta Phase Synchronization between the Human Hippocampus and Prefrontal Cortex Increases during Encoding of Unexpected Information: A Case Study

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Abstract

■ Events that violate predictions are thought to not only modulate activity within the hippocampus and PFC but also enhance communication between the two regions. Scalp and intracranial EEG studies have shown that oscillations in the theta frequency band are enhanced during processing of contextually unexpected information. Some theories suggest that the hippocampus and PFC interact during processing of unexpected events, and it is possible that theta oscillations may mediate these interactions. Here, we had the rare opportunity to conduct simultaneous electrophysiological recordings from the human hippocampus and PFC from two patients undergoing presurgical evaluation for pharmacoresistant epilepsy. Recordings were conducted during a task that involved encoding of contextually expected and un-

expected visual stimuli. Across both patients, hippocampal–prefrontal theta phase synchronization was significantly higher during encoding of contextually unexpected study items, relative to contextually expected study items. Furthermore, the hippocampal–prefrontal theta phase synchronization was larger for contextually unexpected items that were later remembered compared with later forgotten items. Moreover, we did not find increased theta synchronization between the PFC and rhinal cortex, suggesting that the observed effects were specific to prefrontal–hippocampal interactions. Our findings are consistent with the idea that theta oscillations orchestrate communication between the hippocampus and PFC in support of enhanced encoding of contextually deviant information. ■

INTRODUCTION

Unexpected events that violate internal predictions are more likely to be successfully encoded to memory (e.g., Elhalal, Davelaar, & Usher, 2014; Murty & Adcock, 2014; Schomaker et al., 2014; Axmacher et al., 2010). It has been proposed (Lisman & Grace, 2005; Ranganath & Rainer, 2003) that the hippocampus and PFC play a critical role in the detection and formation of memories of contextually unexpected events (e.g., rare events of a specific category that are randomly encountered within most events of a different category; Von Restorff, 1933). Consistent with this idea, fMRI studies in humans have indicated that processing of contextually unexpected information is associated with increased activation in the hippocampus and PFC (and other cortical/subcortical regions; Murty & Adcock, 2014; Murty, Ballard, Macduffie, Krebs, & Adcock, 2013; Yassa & Stark, 2008; Bunzeck & Düzel, 2006; Strange & Dolan, 2001). Interestingly, func-

tional connectivity between the hippocampus and PFC is enhanced during successful memory encoding and retrieval (e.g., Nee & Jonides, 2008; Ranganath, Heller, Cohen, Brozinsky, & Rissman, 2005; Grady, McIntosh, & Craik, 2003). Therefore, a currently unresolved question is whether or how these regions interact during encoding or processing of contextually unexpected events.

Several EEG studies have suggested that neural oscillations in the theta band are enhanced after contextually unexpected events. Studies using intracranial EEG have shown that hippocampal theta power is increased during encoding of contextually unexpected information (Chen et al., 2013; Axmacher et al., 2010). Furthermore, contextually unexpected events elicit increases in scalp-recorded frontal theta power (e.g., Cavanagh & Frank, 2014; Cavanagh, Figueroa, Cohen, & Frank, 2012; Walsh & Anderson, 2012), and recent EEG studies have demonstrated increases in theta phase synchrony between frontal and temporal scalp sites during contextually unexpected stimuli (Harper, Malone, & Iacono, 2017; Lee, Lee, Kim, & Jung, 2014). In light of this evidence, it is possible that theta oscillations facilitate communication between PFC and the hippocampus during encoding of contextually unexpected events.

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Results from other paradigms have indicated that interactions between PFC and the hippocampus could be mediated by theta coupling. For instance, intracranial EEG studies in humans have reported increased theta phase synchronization between PFC and medial temporal lobe cortical regions during virtual navigation and memory retrieval (Watrous, Tandon, Conner, Pieters, & Ekstrom, 2013; Anderson, Rajagovindan, Ghacibeh, Meador, & Ding, 2010; Kahana, Sekuler, Caplan, Kirschen, & Madsen, 1999; but see Raghavachari et al., 2006), but these studies did not report changes in phase synchrony specifically with the hippocampus. Recent studies on memory retrieval in humans using source localization on magnetoencephalography data or combined EEG–fMRI data also suggest that theta oscillations correlate with hippocampal–PFC connectivity (Kaplan et al., 2017; Herweg et al., 2016; Fuentemilla, Barnes, Duzel, & Levine, 2014).

Consistent with the idea that theta oscillations might facilitate communication between PFC and the hippocampus, local field potential recordings in rodents have shown that salient events (e.g., those occurring at choice points in a maze learning task) increase oscillatory power in the theta band (4–8 Hz) within the hippocampus and PFC (e.g., Donnelly et al., 2014; O'Neill, Gordon, & Sigurdsson, 2013; Totah, Jackson, & Moghaddam, 2013; Hasselmo, Bodelón, & Wyble, 2002; Winson, 1978). Furthermore, recordings in rodents and nonhuman primates have also shown that theta oscillations synchronize between the two areas (Brincat & Miller, 2015; Fujisawa & Buzsáki, 2011; Benchenane et al., 2010; Hyman, Zilli, Paley, & Hasselmo, 2005; Jones & Wilson, 2005). For example, enhanced theta phase synchrony between the hippocampus and PFC has been shown during performance of a spatial T-maze task (Benchenane et al., 2010) and during retrieval of object–context associations (Place, Farovik, Brockmann, & Eichenbaum, 2016). These findings in the rodent brain are consistent with the idea that phase synchronization in the theta frequency band is relevant for spike-timing-dependent plasticity (Fell & Axmacher, 2011). However, little is known about the extent to which the findings of frontal–hippocampal synchronization in rodents correspond to activity in the human brain.

In this study, we used intracranial EEG to determine (i) whether human hippocampal–PFC theta phase synchrony is enhanced during processing of contextually unexpected events and (ii) whether hippocampal–PFC theta phase synchrony predicts later memory performance. We used a Von Restorff paradigm (Von Restorff, 1933) in which patients encoded trial-unique images from two different categories (for exemplary trials, see Figure 2A). Importantly, one type of stimuli comprised most encoding stimuli in a given encoding-test block (contextually expected items; e.g., grayscale faces on a red background), and the other type of stimuli only comprised a small percentage (i.e., 14%) of the encoding stimuli in a given encoding-test block (contextually

unexpected items; e.g., grayscale houses on a green background). During the encoding phase, we recorded intracranial EEG simultaneously from the hippocampus and PFC in two patients with pharmacoresistant epilepsy. The locations of the implanted prefrontal electrodes also allowed us to explore whether theta phase synchronization with the hippocampus might be evident with specific subregions of PFC. In addition, we also investigated phase synchronization between PFC and sites in the rhinal cortex.

METHODS

We recorded intracranial EEG from two pharmacorefractory epileptic patients at the Department of Epileptology at the University of Bonn, Germany. Both patients (one woman; 46 and 48 years old) were implanted with bilateral depth electrodes in the hippocampus and the adjacent rhinal cortex as well as with bilateral subdural electrodes covering parts of PFC (i.e., one frontopolar and one frontolateral electrode strip bilaterally covering rostral/anterior and lateral PFC regions, respectively; see Figure 1). From the larger sample of patients reported in Axmacher et al. (2010), the two patients were the only patients who had both implanted hippocampal and PFC electrodes. Details about the patients and analyses of ERPs and oscillatory power from hippocampal sites in these two patients are presented in Axmacher et al. (2010). Because epileptic seizures were focused on left hippocampal and surrounding medial temporal lobe areas in one patient and left medial temporal lobe areas and left temporolateral areas in the other patient, we only considered data from the hippocampal, rhinal, and PFC electrodes on the right hemisphere. The local ethics

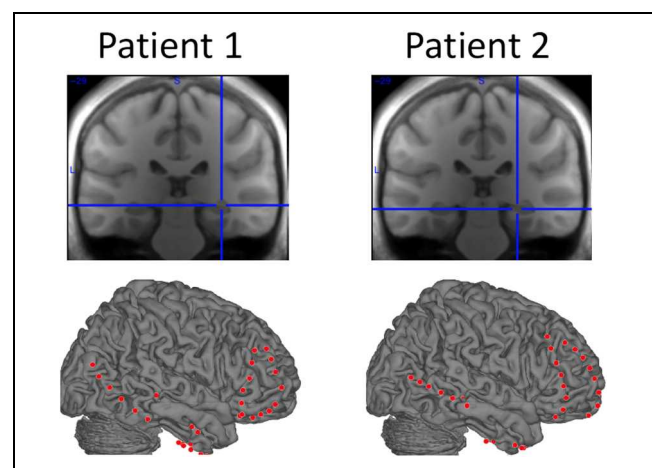


Figure 1. Locations of hippocampal and prefrontal electrodes. On the top, the location of the selected hippocampal electrode is depicted for each patient (Patient 1: MNI = 32, -29, -7; Patient 2: MNI = 26, -29, -10). On the bottom, all implanted subdural strip electrodes covering the right hemisphere are depicted for each patient. Only the frontopolar and frontolateral strips were analyzed for each patient.

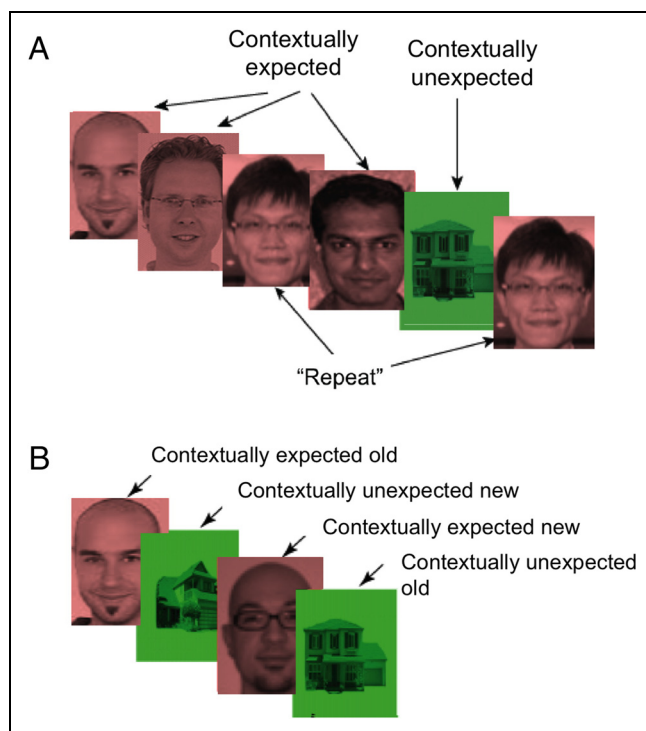


Figure 2. Experimental procedure. (A) During the encoding phase for which iEEG results are reported here, patients encoded images of stimuli that comprised most encoding stimuli (contextually expected items), and the other type of stimuli only comprised a small percentage (contextually unexpected items). Categories (i.e., faces, houses) and colors (i.e., red, green) of contextually expected and unexpected stimuli were counterbalanced across blocks in each patient. (B) After an encoding block, patients completed a recognition memory test.

committee approved the study, and both patients gave written informed consent.

Both patients took part in a variant of a Von Restorff paradigm (Von Restorff, 1933; for details of the experimental procedure, see Axmacher et al., 2010). During the encoding phase for which iEEG results are reported here, patients encoded trial-unique images from two different categories (for exemplary trials, see Figure 2A). Importantly, one type of stimuli comprised most encoding stimuli in a given encoding-test block (contextually expected items; e.g., grayscale faces on a red background as shown in Figure 2A), and the other type of stimuli only comprised a small percentage (i.e., 14%) of the encoding stimuli in a given encoding-test block (contextually unexpected items; e.g., grayscale houses on a green background as shown in Figure 2A). Categories and colors of contextually expected and unexpected stimuli were counterbalanced across blocks in each patient. After the encoding phase, patients completed a recognition memory test for these images (Figure 2B). Memory accuracy (i.e., hits – false alarms collapsed across confident old and unconfident old responses) was higher for contextually unexpected compared with expected events in Patient 1 (40% vs. 35%) but not in Patient 2 (44% vs. 53%).

First, we restricted our iEEG analyses to contextually unexpected (Patient 1: 32 trials; Patient 2: 15 trials) and contextually expected items (Patient 1: 68 trials; Patient 2: 45 trials) that were later correctly recognized in the recognition memory test (i.e., collapsed across correct confident old and unconfident old responses), to examine effects of contextual unexpectedness. This approach gave us a sufficient number of trials and did not confound effects driven by contextual unexpectedness with memory encoding. Second, we asked whether any potential theta phase synchronization effects further predict later memory. To this end, we compared the later remembered items (from the previous analysis) with the later forgotten items separately in the contextually unexpected condition (forgotten items: Patient 1, 17 trials; Patient 2, 25 trials) and the contextually expected condition (forgotten items: Patient 1, 18 trials; Patient 2, 29 trials). Forgotten trials included items with incorrect confident new and unconfident new responses as well as items for which the patients did not give any response during the recognition test.

Because electrode placement varied across patients because of the clinical needs of each patient, we focused our analyses on hippocampal contacts that were most consistently localized across the two patients. That is, we first selected one hippocampal electrode per patient that had maximal anatomical overlap between the two patients. The selected hippocampal electrode pair (one electrode from each patient) had the smallest Euclidean distance between the two patients (7-mm distance; Patient 1: Montreal Neurological Institute [MNI] = 32, –29, –7; Patient 2: MNI = 26, –29, –10; see Figure 1). We then used the EEGLAB toolbox (Delorme & Makeig, 2004) to segment the iEEG data into epochs from –2 to +3 sec relative to the onset of all items. To preprocess these data, first, we used an automated artifact detection procedure implemented in EEGLAB, in which EEG activity that exceeded more than three 3 SDs from the mean on that electrode or 5 SDs across all electrodes was excluded from the analyses (Gruber, Watrous, Ekstrom, Ranganath, & Otten, 2013). Second, in line with our original data set (Axmacher et al., 2010), we then visually inspected the hippocampal and prefrontal raw data and further manually discarded trials containing EEG artifacts and epileptiform activity from any further analyses (i.e., trials discarded because of artifacts or epileptic signals detected in a given channel were also excluded from the analysis for all other electrodes).

We also excluded data from the first electrode of each PFC electrode strip (i.e., most inferior electrode) for both patients because of a very low signal-to-noise ratio as compared with all other remaining PFC electrodes (i.e., no visible event-related evoked responses across contextually unexpected and expected trials). Artifact-free iEEG data were then imported into the Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) for further analysis. First, standard time–frequency decomposition

was performed on artifact-free raw EEG data to obtain power and phase information. We used a Morlet wavelet decomposition method with a width of 5 cycles in individual frequencies. Decomposition was conducted within the epoch period of -0.2 to 1.2 sec (t_1 = onset of event) in steps of 0.02 sec and in the frequency range of 2 – 20 Hz.

Second, to address the role of theta phase synchrony between the hippocampus and PFC, we calculated phase synchrony indices between the previously selected hippocampal electrode and each of the artifact-free frontal electrodes, resulting in 14 hippocampal–PFC electrode pairs for each patient. Phase synchrony was separately quantified for all four conditions (contextually unexpected remembered, contextually unexpected forgotten, contextually expected remembered, and contextually expected forgotten) using the debiased estimator of the squared weighted phase lag index (d-WPLI) implemented in Fieldtrip. The d-WPLI has the advantage that it alleviates problems related to volume conduction and other noise-related issues (Vinck, Oostenveld, van Wingerden, Battaglia, & Pennartz, 2011).

To statistically determine whether contextually unexpected compared with expected items show a significant theta phase synchrony increase, we used a nonparametric statistical approach that randomly permutes condition labels to correct for multiple comparisons across electrode pairs. Analyses were conducted separately in each patient for all data points within a selected time–frequency range (time range = -0.2 to 1.2 sec, frequency range = 2 – 20 Hz). This analysis approach had the strength to reveal significant time–frequency clusters without prior selection of a specific time–frequency bin of interest. The steps are as follows: (1) We computed the d-WPLI values within the selected time–frequency range for each condition (to use an identical approach as for the surrogate data, we randomly selected equal trial numbers from two conditions of interest based on the minimum number of trials in one condition). We then computed the difference of the d-WPLI values between the conditions of interest (i.e., first analysis: contextually unexpected vs. expected items; second and third analyses: remembered vs. forgotten items in the contextually unexpected and contextually expected conditions, separately). Thereby, we obtained the empirical difference in theta phase synchrony (i.e., d-WPLI) between two conditions. (2) We shuffled trial labels by randomly selecting equal trial numbers from the two conditions based on the minimum number of trials in one condition, calculated surrogate phase synchrony values for all 14 electrode pairs, took the difference between the surrogate conditions for all 14 electrode pairs, and saved the maximum surrogate phase synchrony difference across all 14 electrode pairs (i.e., electrode-pair_{max}). (3) Step 2 was repeated 500 times. On the basis of the 500 permutations, we created a null distribution of all electrode-pair_{max} difference values and determined the alpha cutoff point ($p < .05$, one-sided; i.e., 475th data point in surrogate difference distribution) to test the statistical

significance of the empirical theta phase synchrony values for all electrode pairs. This stringent approach allowed us to correct for multiple comparisons across electrodes.

RESULTS

As shown in Figure A1, in both patients, permutation tests that corrected for multiple comparisons revealed that frontopolar (within Brodmann's area 10) and dorso-lateral (within Brodmann's area 46) prefrontal electrode sites showed significantly increased theta phase synchrony with the hippocampus during encoding of contextually unexpected compared with expected items. Figure 3 depicts one selected hippocampal–frontopolar electrode pair per patient showing phase synchronization increases for contextually unexpected compared with expected items in the theta frequency range (~ 3 – 8 Hz; black contours show the permutation-based significant difference clusters in Figure 3A). We found that the theta phase synchronization increase is specific to contextually unexpected items (Figure 3B) and absent in contextually expected items (Figure 3C).

In a second set of analyses, we investigated whether the increased theta phase synchronization related to contextual unexpectedness predicted later memory performance. Importantly, in the “contextually unexpected” condition, across both patients, permutations tests revealed a significant increase in hippocampal–frontopolar theta phase synchronization for later remembered compared with later forgotten unexpected information (Figure 4A). As such, the significant cluster of the contextually unexpected subsequent memory effect overlapped with the significant time–frequency cluster of the contextually unexpected–expected contrast (see Figure 4 for the same hippocampal–frontopolar electrode pairs shown in Figure 3). In contrast, the subsequent memory analysis for the “contextually expected” condition only showed smaller significant clusters that did not overlap in the time–frequency domain with the original clusters from the contextually unexpected–expected contrast (Figure 4B). For completeness, Figure A2 shows all 14 electrode pairs for the encoding-related phase synchronization in the contextually unexpected condition.

To examine whether the theta phase synchrony effects were specific to hippocampal–PFC interactions, we performed control analyses in which we quantified theta phase synchrony between rhinal and PFC electrodes. We selected an electrode contact for each patient from the rhinal cortex (perirhinal/entorhinal cortex) based on the smallest Euclidean distance between rhinal contacts in both patients resulting in a 9-mm distance between both patients (distance between rhinal and hippocampal contact: 41 and 36 mm for Patients 1 and 2, respectively). Importantly, permutation tests that corrected for multiple comparisons across electrode pairs revealed that the frontal electrodes that showed increases in theta phase synchrony with the hippocampus did not show

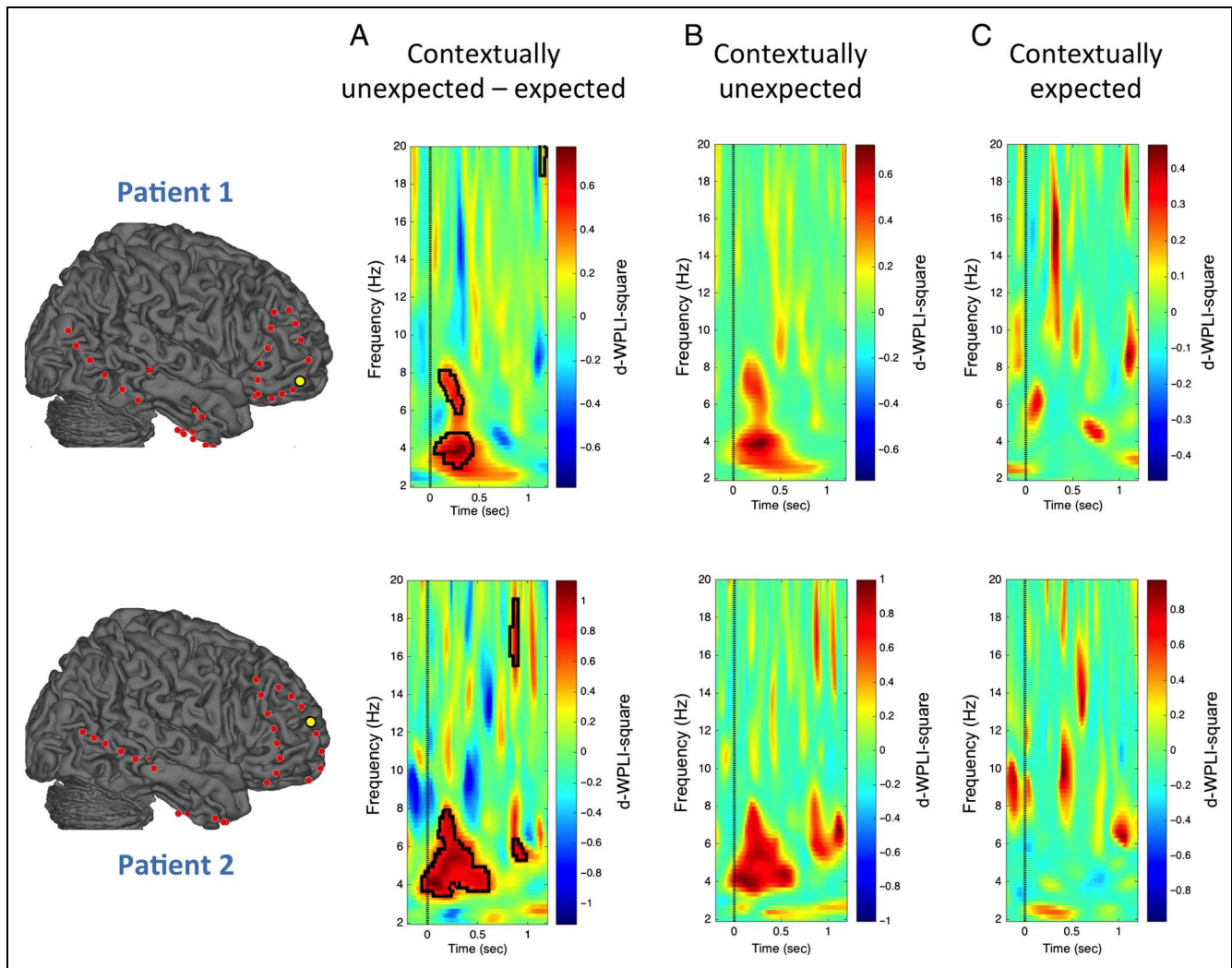


Figure 3. Increases in hippocampal–prefrontal theta phase synchrony for contextually unexpected compared with expected information for one selected frontopolar electrode per patient (highlighted in yellow). In both patients, frontopolar and dorsolateral prefrontal electrode sites showed significantly increased theta phase synchrony with the hippocampus during encoding of contextually unexpected compared with expected items (see Figure A1 for all 14 hippocampal–PFC electrode pairs). Phase synchrony was measured via the debiased WPLI-square estimator (d-WPLI) (Vinck et al., 2011). Top row depicts findings for Patient 1 and bottom row depicts findings for Patient 2. (A) Significant clusters revealed via permutation tests are depicted with black contours ($p < .05$ family-wise error corrected). (B) Theta phase synchronization was evident for contextually unexpected events and (C) absent in contextually expected events.

enhanced theta phase synchrony with the rhinal cortex for contextually unexpected compared with contextually expected trials.

DISCUSSION

Our study demonstrates that theta phase synchrony between the hippocampus and PFC is enhanced during unexpected, contextually deviant events. Moreover, particularly at sites in the frontopolar cortex, results from both participants converged in revealing that hippocampal–frontopolar synchronization predicted later memory performance. These findings are consistent with the idea that theta oscillations facilitate communication between PFC and the hippocampus in support of successful memory encoding.

Although electrophysiological recording studies in rodents and nonhuman primates have provided evidence for task-evoked changes in theta synchronization between the hippocampus and PFC (Place et al., 2016; Brincat & Miller, 2015; Fujisawa & Buzsáki, 2011; Benchenane et al., 2010; Hyman et al., 2005), it is worth noting that nonhuman and human electrophysiological studies typically assess synchrony in different ways. Studies in rodents often measure synchrony via single-unit spiking activity that is phase-locked to theta oscillations or via amplitude-based coherence of local field potentials between two regions (e.g., Benchenane et al., 2010; Jones & Wilson, 2005). Human studies, in contrast, commonly measure synchrony via phase alignment of theta oscillations between distant brain regions (e.g., Kaplan et al., 2017; Backus, Schoffelen, Szebényi, Hanslmayr, & Doeller, 2016; Watrous et al.,

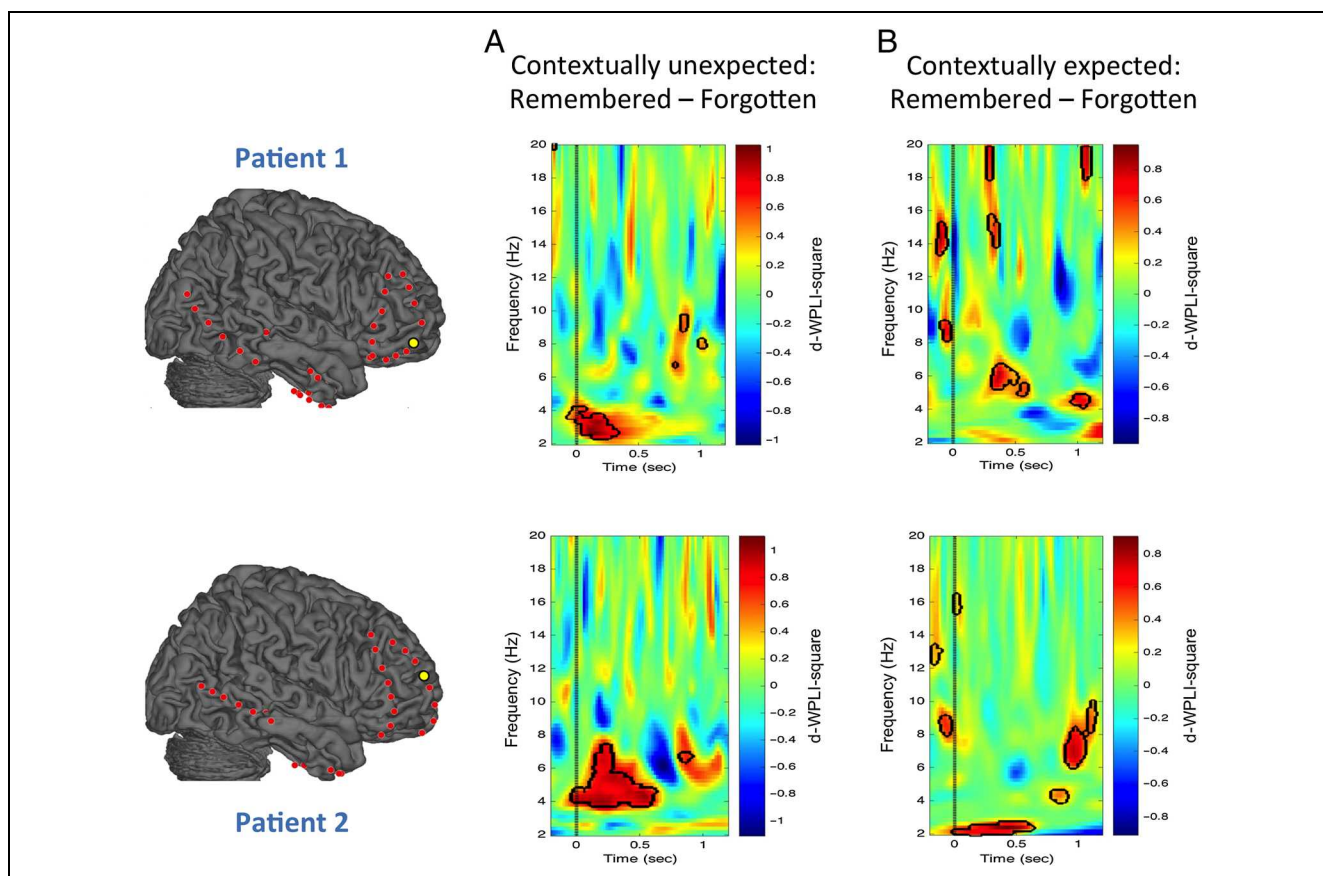


Figure 4. Subsequent memory analyses for the ‘contextually unexpected’ and ‘contextually expected’ condition. Across both patients, permutation tests revealed strong encoding-related hippocampal-frontopolar theta phase synchronization (same hippocampal-PFC electrode pairs as shown in Figure 3) in the ‘contextually unexpected’ condition that overlapped with the time-frequency cluster of the previously observed theta phase synchronization increase for contextually unexpected events (see Figure A2 for all 14 hippocampal-PFC electrode pairs). In contrast, encoding-related theta phase synchronization in the “contextually expected” condition was limited to small clusters that did not overlap with the previously reported phase synchronization for unexpected events.

2013). Despite these methodological differences in the measurement of synchrony, our findings in humans converge with findings in rodents in that they support the idea that theta synchrony facilitates interactions between the hippocampus and PFC and thereby facilitates memory formation.

Our findings are consistent with recent findings in rodents (Place et al., 2016) that have shown that hippocampal-PFC phase synchronization represents long-range communication. On the basis of the findings by Place et al. (2016) that the mnemonic operation determines the direction of information flow between the two regions, we speculate that information flow from the hippocampus to PFC might underlie the encoding of unexpected events into memory. However, our analyses do not allow making any claim about the directionality, and more advanced analyses would be needed to address this question.

It could be argued that theta synchronization might be a ubiquitous phenomenon during encoding, but at least two aspects of our findings are not consistent with this idea. First, theta synchrony between the two regions was larger for contextually unexpected compared with

expected events, and second, this synchrony increase was specific between PFC and the hippocampus but did not extend to a cortical medial temporal lobe region (i.e., no evidence for rhinal-PFC theta synchrony). Therefore, our findings suggest that increased theta synchrony might be specific to a brain network (involving PFC and hippocampus) that detects the salience of information rather than being a ubiquitous property during encoding.

We found an increase in theta phase synchrony during an early period during the presentation of a contextually unexpected event. Further control analyses of time-frequency power for the hippocampus and PFC contacts did not reveal consistent early theta power increases for contextually unexpected events in the two patients. It is therefore unlikely that theta power effects in the two regions drove the phase synchronization findings. However, the early theta hippocampal-PFC synchrony coincides with our previously shown early ERP finding in the human hippocampus (Axmacher et al., 2010). Therefore, the increase in theta synchrony between PFC and the hippocampus, together with this early hippocampal ERP, might suggest an early detection

process that is elicited when expectations are violated and that the ongoing encoding processes need to be flexibly adapted toward the contextually unexpected information (cf. Axmacher et al., 2010). As pointed out in our earlier study (Axmacher et al., 2010), we cannot rule out that a third source might have driven the observed effect between the hippocampus and PFC. For example, as unexpected information depends on activity within a cortico-mesolimbic circuit, it would be interesting to test how other regions within the circuit might affect hippocampal–PFC synchrony (e.g., Fujisawa & Buzsáki, 2011; Benchenane et al., 2010). Because of the sparse implantation scheme of intracranial EEG, this method is not ideally suited to investigate this question.

Although the understanding of the direct anatomical connections between the hippocampus and frontopolar cortex is complicated by the fact that frontopolar cortex may be differentially organized in humans, as compared with nonhuman primates or rodents (Semendeferi, Lu, Schenker, & Damasio, 2002), one possible route could be via the nucleus reuniens of the ventral midline thalamus (Bokor, Csáki, Kocsis, & Kiss, 2002; Herkenham, 1978), which has been shown to support long-term memory formation (Barker & Warburton, 2018). Alternative

routes could be via the entorhinal cortex and parahippocampal cortex/retrosplenial cortex (Ranganath & Ritchey, 2012).

One limitation of this study is that only two patients had electrodes placed in both the hippocampus and PFC. It would be beneficial for future studies to investigate this question with a larger sample and a sufficient number of trials to test the reproducibility of the data. In addition, future research would need to address how the observed theta phase synchronization for contextually unexpected information that predicts later memory generalizes to different forms of salient stimuli (e.g., novel or rewarded information).

In conclusion, we have shown that contextually unexpected information elicits increased theta phase synchrony between the hippocampus and frontopolar cortex, and this increase in theta phase synchrony is associated with successful memory formation. Consistent with the literature on the relationship between theta activity and memory (for reviews, see Hsieh & Ranganath, 2014; Düzel, Penny, & Burgess, 2010), we suggest that theta synchrony between the hippocampus and PFC may be an important neural mechanism that helps to facilitate memory formation of novel, unexpected information.

APPENDIX

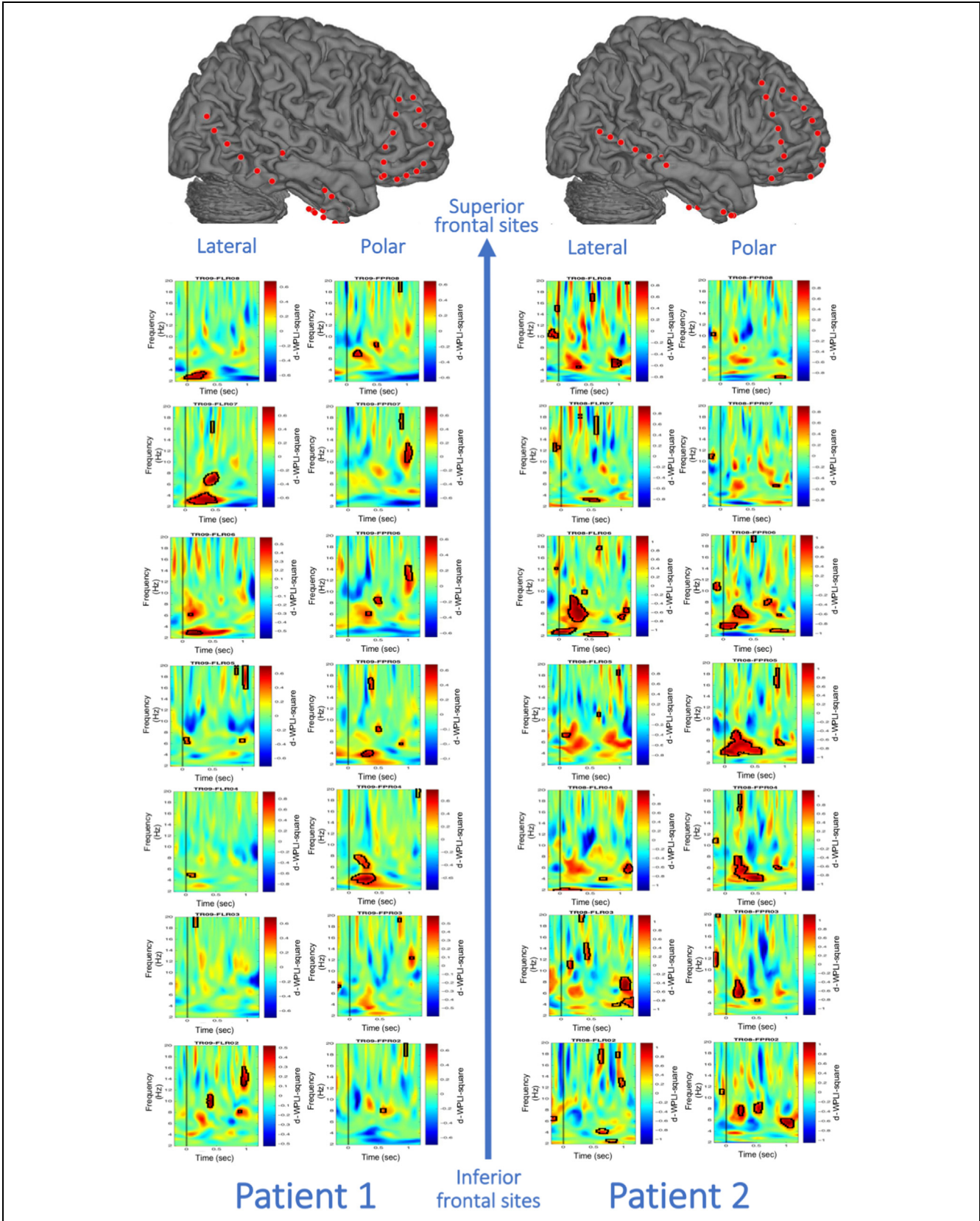


Figure A1. Increase in theta phase synchronization for contextually unexpected compared with contextually expected events between the hippocampus and frontopolar and dorsolateral PFC electrode sites. All selected 14 hippocampal–PFC electrode pairs are shown. Significant clusters revealed via permutation tests are depicted with black contours.

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